The Trigonometric Parallax of the Brown Dwarf Planetary System 2MASSW J1207334-393254

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ABSTRACT

We have measured a trigonometric parallax to the young brown dwarf 2MASSW J1207334-393254. The distance ($54.0^{+3.2}_{-2.8}$ pc) and space motion confirm membership in the TW Hydrae Association. The primary is a $\sim 25 M_{jup}$ brown dwarf. We discuss the "planetary mass" secondary, which is certainly below the deuterium-burning limit but whose colors and absolute magnitudes pose challenges to our current understanding of planetary-mass objects.

Subject headings: stars: low-mass, brown dwarfs — planetary systems — stars: individual (2MASSW J1207334-393254) — Galaxy: open clusters and associations: individual: TW Hydrae Association

1. Introduction

The M8 brown dwarf 2MASSW J1207334-393254 (hereafter 2M1207A) is proving to be an important system for studying the formation of substellar objects. It was discovered by Gizis (2002) in a search for brown dwarf members of the ~ 10 Myr old TW Hydrae Assocation (Webb et al. 1999). 2M1207A is a very-low-mass substellar analog to a classical T Tauri star: It has broad, variable Hα emission due to accretion (Mohanty et al.

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2003; Scholz & Jayawardhana 2006), mid-infrared excess due to a disk (Sterzik et al. 2004; Riaz et al. 2006), ultraviolet emission due to hot accreted gas and warm circumstellar molecular hydrogen gas (Gizis et al. 2005), and forbidden oxygen emission due to an outflow(Whelan et al. 2007). Despite its youth, it is not detected in X rays (Gizis & Bharat 2004) or radio (Osten & Jayawardhana 2006), so is apparently relatively magnetically inactive.

Chauvin et al. (2004) discovered a red companion (2M1207B), 5 magnitudes fainter in the K band. Common proper motion confirms that this is a bound pair (Chauvin et al. 2005; Song et al. 2006) with a separation of 773 ± 1.4mas. The secondary has a late-L spectral type (Mohanty et al. 2007). The inferred luminosity implies a mass $\sim 5 M_J$ (Chauvin et al. 2004; Song et al. 2006), although Mohanty et al. (2007) suggest that the secondary is 8 ± 2 jupiter masses and viewed through an edge-on disk.

Because the TWA is a relatively nearby, loose association there has been some confusion on the distance to the system. Chauvin et al. (2004) adopted a distance of 70 pc, on the basis of theoretical models of brown dwarf evolution. The Hipparcos distance of TW Hya itself is 56^{+8}_{-6}pc (Perryman et al. 1997). Mamajek (2005) used the moving cluster distance method to estimate the distance to 2M1207A to be 53 ± 7 pc, while Song et al. (2006) used the same method, but an updated proper motion and a different group membership list to estimate 59 ± 7 pc. With uncertainties in the distance to the TW Hya group of $\sim 15\%$, firm conclusions about the natures of 2M1207 A and B, as well as other members of the group, have been elusive." Here we present the first trigonometric parallax for 2M1207A. We confirm that it is a member of the TW Hya Association and put put constraints on the planet candidate 2M1207B.

2. Parallax Results and Dicussion

Observations of 2M1207A in the I_{KC} band were obtained at the CTIO 0.9m telescope by the RECONS group via the SMARTS Consortium. There are 54 parallax frames obtained over 2.14 years. The observing techniques and data reduction are fully described by Jao et al. (2005). The resulting relative parallax is $\pi_{rel} = 17.93 \pm 1.03$ mas. VRI photometry was obtained in July 2007 on five nights using the same telescope and reduced as described in Jao et al. (2005). We estimate the correction to absolute parallax to be 0.58 ± 0.05 mas on the basis of photometry of the seven reference stars (Table 1.) The absolute parallax is therefore 18.51 ± 1.03 mas, for a distance of $54.0^{+3.2}_{-2.8}$pc. The observed proper motion is 66.7 ± 1.5 masyr^{-1} at position angle $\theta = 250.0 \pm 2.4$ degrees.

The distance and proper motion of 2M1207 is consistent with TWA membership. The

position angle expected for motion towards Mamajek (2005)'s TWA convergent point is 251.4 degrees, consistent with the measured proper motion. Using Mohanty et al. (2003)'s radial velocity of $+11.2 \pm 2.0$ km s^{-1} for 2M1207A, the (U,V,W) space velocities are $(-8, -18, -4)$ kms^{-1}, consistent with Mamajek's centroid group value of $(-10.2, -17.1, -5.1)$ kms^{-1} . In particular, the measured distance rules out any association with the background Lower Centaurus Crux discussed by Mamajek (2005). Using Song et al. (2006)'s measurements and our distance, the projected separation is 41.7 ± 2.3 A.U.

The Primary and its Disk: Mohanty et al. (2007) found 2M1207A to be $24 \pm 6 M_J$ brown dwarf. Because they used Mamajek's value of 53 pc as the distance, this mass is not changed significantly by a distance increase of 2%: 2M1207A is best understood as a $\sim 25 M_J$ brown dwarf. The disk parameters derived by Riaz & Gizis (2007) also remain unchanged because they used the same distance. The observed $V - K_s = 8.00 \pm 0.19$ is consistent with the M8 spectral type and suggests the accretion rate at the time was $\lesssim 10^{-11} M_{\odot}$yr^{-1} (see Figure 4 of Riaz & Gizis 2007.) In Figure 1, we plot the H-R diagram of the local field population and 2M1207A. Like the young M dwarf AU Mic (Gl 803), 2M1207A lies ~ 1.5 magnitudes above the main sequence in the M_V vs $V - K$ diagram, confirming youth.

The Secondary: The usual procedure for analyzing 2M1207B is to assume a bolometric correction appropriate to late-L dwarfs, and then fit the luminosity to evolutionary models. Chauvin et al. (2004) estimated $5 \pm 2 M_J$ for 70 pc, Song et al. (2006) estimated $5 \pm 3 M_J$ for 59 pc, and Mamajek (2005) estimated $3 - 4 M_J$ for 53 pc. The trigonometric parallax would therefore support the last two estimates. Mohanty et al. (2007), however, noted an inconsistency with this procedure. They argued that their H and K-band near-infrared spectra of 2M1207B were best fit by an effective temperature of 1600 ± 100K. However, for the $3 - 5 M_J$ fits, the expected effective temperature is more like $1000 - 1200$ K. They suggest the best resolution is that 2M1207B is viewed through an edge-on gray disk, and that therefore it is more luminous than otherwise estimated. 2M1207B is then a $8 \pm 2 M_J$ planetary mass brown dwarf. The wide separation and mass ratio ($q \approx 0.2 - 0.3$) suggests this planetary-mass object did not form through core accretion (Chauvin et al. 2005).

Without rejecting the possibility of a edge-on disk, we argue that available evidence does not rule out a low temperature for 2M1207B. In Figure 2, we plot colors and absolute magnitudes for late-M, L and T dwarfs with parallaxes (Perryman et al. 1997; Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004; Henry et al. 2006). All the previous attempts to fit 2M1207B noted that it is red compared to field brown dwarfs, which can be attributed to having more dust in the photosphere. The faintness at J-band measured by Mohanty et al. (2007) ($\Delta J = 7.0 \pm 0.2$) is supported by the NICMOS F110M measurement of Song et al. (2006) ($\Delta m_{110M} = 7.17 \pm 0.15$). Chauvin et al. (2004) measured $\Delta K = 4.98$ and $K =$

16.93 ± 0.11 for 2M1207B. On the other hand, it is clear from Mohanty et al.'s (2007) ($SN \approx 3 - 10$) spectrum that there is deep water absorption but little methane absorption. We conclude that 2M1207B has a spectral energy distribution that is L-type, but very red. Reversing the usual procedure, in Figure 3 we plot the required K-band bolometric correction required to fit the Chabrier et al. (2000) models at an age of 10 Myr. Observed bolometric corrections for field L and T dwarfs from Golimowski et al. (2004) as a function of temperature for an assumed age of $3Gyr$ are also shown. The L to T transition is believed to occur at $\sim$ 1300K, and can be marked in Figure 3 by the change in bolometric corrections. The transition is related to the change in dust properties in photosphere (see Kirkpatrick 2005 for a review), and some of the first fits to late-L dwarf spectra gave incorrect values of $\gtrsim$ 1600K due to the failure of cooler models to resemble the real spectra. This simply reflects the extreme difficulty of modelling the temperature range 1200-1400K, and indeed In light of this, no models succeed in fully explaining both the blue hook and brightening in J-band of field T dwarfs. Analysis of the luminosity (see Kirkpatrick) has been the most reliable way to derive temperatures. This history suggests to us that the existing fit must be viewed with caution — while apparently very good, it is inconsistent with the absolute magnitudes unless an edge-on disk is invoked. Although Mohanty et al. show that the DUSTY models do fit the observed color of 2M1207B, it must be noted that the same models predict very red colors for field L dwarfs, which are not observed. Indeed, Chabrier et al. (2000) note that "the DUSTY and COND models represent extreme situations which bracket the more likely intermediate case resulting from complex, and presently not understood, thermochemical and dynamical processes." We think it plausible that existing DUSTY models fail to properly model the dust in low surface gravity dwarfs, and that 2M1207B might therefore be $\sim$ 1200K, as expected for the $\sim 5M_{jup}$ model. As an example how this might occur, we note that Tsuji (2005) invokes a parameter, T_{cr}, that characterizes the thickness of the clouds, and argues that the wide range of colors for field objects near 1400K is due to changes in this parameter in otherwise similar brown dwarfs. In one case, Tsuji (2005) is able to fit an L6.5 dwarf with $T_{eff} =$ 1700K or $T_{eff} =$ 1300K (without methane absorption) by varying T_{cr} by only 100K. Evidently an extremely red color like 2M1207B could be obtained for a low T_{eff} with $T_{cr} <$ 1700K – that is, a very thick cloud compared to field L dwarfs. This would be the opposite situation from field T dwarfs, where the cloud becomes thinner (T_{cr} increases.) Similarly, in the Marley et al. (2002) models, a parameter, f_{rain}, represents sedimentation, and redder colors are produced by smaller values of f_{rain} (i.e., less precipitation and thicker clouds.) Regardless of how the proper degree of dust is produced, if our speculation that $T_{eff} \approx$ 1200K is correct, the implied $BC_K \approx 2.5$ would require that more of 2M1207B's energy is escaping at wavelengths longward of 3 microns than in field L dwarfs. In any case, the observed colors and spectrum do not match any field brown dwarf, so there is not much doubt that atmosphere is dustier, but a low temperature remains speculative.

Unfortunately, there is a third problem with estimating the mass of 2M1207B. Marley et al. (2007) have investigated the dependence of the structure models to the initial conditions, and found that the luminosity is very sensitive to the initial conditions for up to 100 Myr. In specifically discussing the case of 2M1207B, they note that for a "warm start" rather than usually assumed "hot start," the best fit mass is $8M_{jup}$ rather than $5M_{jup}$. The situation, therefore, is that given the now known distance, 2M1207B may be $\sim 5 \pm 2M_{jup}$ *if* current structural models are correct, the red color implies a cool temperature, and there is no disk, but both Mohanty et al. (2007) and Marley et al. (2007) present plausible scenarios in which the mass is higher.

3. Conclusions

We have measured the trigonometric parallax of 2M1207 and found that the distance and space motion are consistent, as expected, with membership in the TW Hydrae Association. Indeed, 2M1207 now has a more precise distance determination than TW Hya itself. There are no difficulties in modelling the primary: It is a $\sim 25M_{jup}$ mass brown dwarf that is accreting from a circumstellar disk. The faint secondary remains problematic. Because we do not know the appropriate initial conditions, do not have a model atmosphere that reproduces the colors, and do not know whether or not it is observed through a disk, a case can be made that 2M1207B's mass is as low as $3M_J$ or as high as $8M_J$. Our best estimate is $\sim 5M_{jup}$ if 2M1207B is not viewed through a disk. Further study of this planetary mass object is needed; we particularly need to know if it has an effective temperature of 1600K , 1200K, or even less.

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Table 1. 2M1207

Item	2M1207A	2M1207B
V	19.95 ± 0.19	$\cdots$
R	17.99 ± 0.07	$\cdots$
I	15.92 ± 0.05	$\cdots$
J	13.00 ± 0.03	20.0 ± 0.2
H	12.39 ± 0.03	18.09 ± 0.21
K	11.95 ± 0.03	16.93 ± 0.11
π_{rel} (mas)	17.93 ± 1.03	
π_{ref} (mas)	0.58 ± 0.05	
π_{abs} (mas)	18.51 ± 1.03	
M_V	16.29 ± 0.22	$\cdots$
M_J	9.34 ± 0.12	16.3 ± 0.3
M_H	8.73 ± 0.12	14.4 ± 0.3
M_K	8.29 ± 0.12	13.27 ± 0.16
Mass (M_{jup})	~ 25	$\sim 3 - 8$

Note. — VRI and astrometry from this paper; JHK for 2M1207A from 2MASS Skrutskie et a. (2006); J for 2M1207B from Mohanty et al. (2007); H and K from Chauvin et al. (2004)

REFERENCES

Chauvin, G., et al. 2004, A&A, 425, L29

Chauvin, G., et al. 2005, A&A, 438, L25

Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464

Dahn, C.C., et al. 2002, AJ, 124, 1170

Gizis, J.E., 2002, ApJ, 575, 484

Gizis, J.E., & Bharat, R. 2004, ApJ, 608, L113

Gizis, J.E., Shipman, H.L., & Harvin, J.A. 2005, ApJ, 630, L89

Golimowski, D.A., et al. 2004, AJ, 127, 3516

Henry, T.J., Jao, W.-C., Subasavage, J.P., Beaulieu, T., Ianna, P.A., Costa, E., & Mendez, R.A. 2006, AJ, 132, 2360

Jao, W.-C., et al. 2005, AJ, 129, 1954

Jayawardhana, R., Ardila, D. R., Stelzer, B., & Haisch, K.E. 2003, AJ, 126, 1515

Kirkpatrick, J.D. 2005, ARA&A, 43, 195

Mamajek, E.E. 2005, ApJ, 634, 1385

Marley, M.S., Seager, S., Saumon, D., Lodders, K., Ackerman, A.S., Freedman, R.S., & Fan, X. 2002, ApJ, 568, 335

Marley, M.S., Fortney, J.J., Hubickyj, O., Bodenheimer, P., & Lissauer, J.J. 2007, AJ, 655, 541

Mohanty, S., Jayawardhana, R., & Barrado y Navascues, D. 2003, ApJ, 593, L109

Mohanty, S., Jayawardhana, R., Huelamo, N., & Mamajek, E. 2007, ApJ, 657, 1064

Osten, R.A., & Jayawardhana, R. 2006, ApJ644, L67

Perryman, M.A.C., et al. 1997, A&A, 323, L49

Riaz, B., Gizis, J.E., & Hmiel, A. 2006, ApJ, 639, L79

Riaz, B., & Gizis, J.E. 2007, ApJ, 661, 354

Scholz, A., & Jayawardhana, R. 2006, ApJ, 638, 1056

Skrutskie, M.F., et al. 2006, AJ, 131, 1163

Song, I., et al. 2006, ApJ, 652, 724

Sterzik, M.F., Pascucci, I., Apai, D., van der Bliek, N, & Dullemond, C.P. 2004, A&A, 427, 245

Tinney, C.G., Burgasser, A.J., Kirkpatrick, J.D. 2003, AJ, 126, 975

Tsuji, T. 2005, ApJ, 621, 1033

Webb, R.A., et al. 1999, ApJ, 512, L63

Whelan, E.T., Ray, T.P., Randich, S., Bacciotti, F., Jayawardhana, R., Testi, L., Natta, A., & Mohanty, S. 2007, ApJ, 659, L45

Vrba, F.J., et al. 2004, AJ, 127, 2948

Zuckerman, B., Song, I., Bessell, M.S., & Webb, R.A. 2001, ApJ, 562, L87

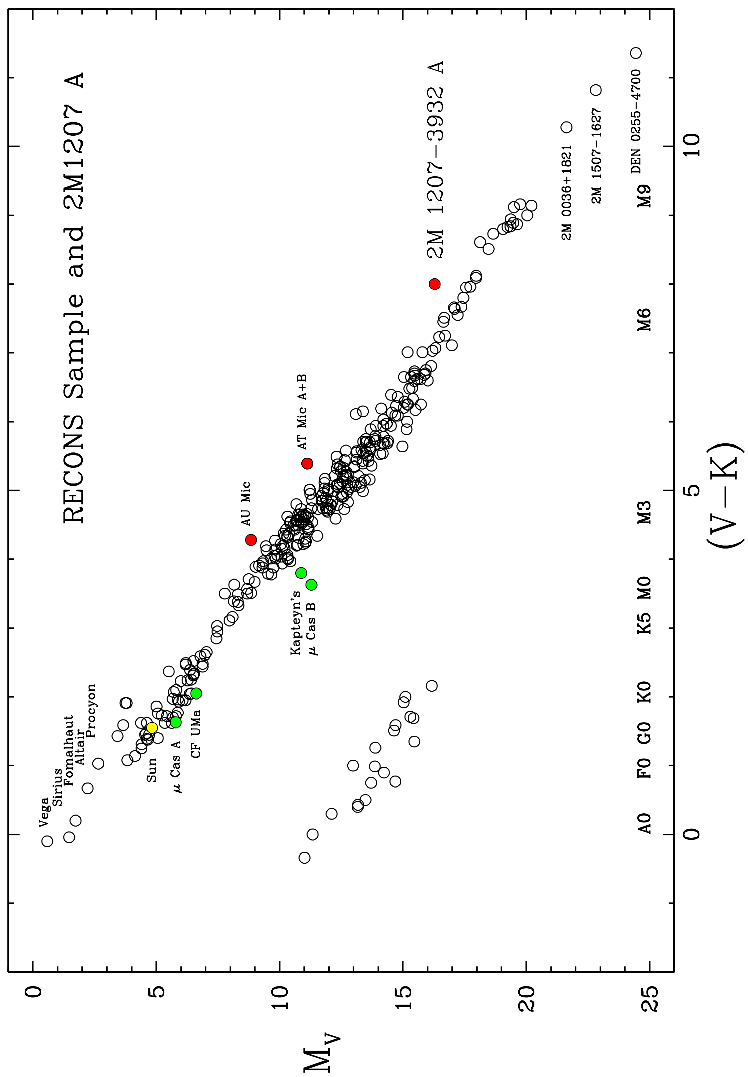

Fig. 1.— 2M1207A is plotted among the known members of the RECONS 10 pc sample (Henry et al. 2006). Highlighted points include the Sun, the three subdwarf systems μ Cas AB, CF UMa, and Kapteyn's Star, and the triple system AU Mic/AT Mic AB. The latter system is estimated to be $\sim$ 12 Myr in age Zuckerman et al. (2001), causing the points to be elevated above the main sequence, as expected (the point for AT Mic AB actually represents each component, not the combined light of both components — the two stars are nearly identical in brightness). Because of youth, 2M1207 A is also elevated above the main sequence, much like its nearer counterparts, AU Mic and AT Mic.

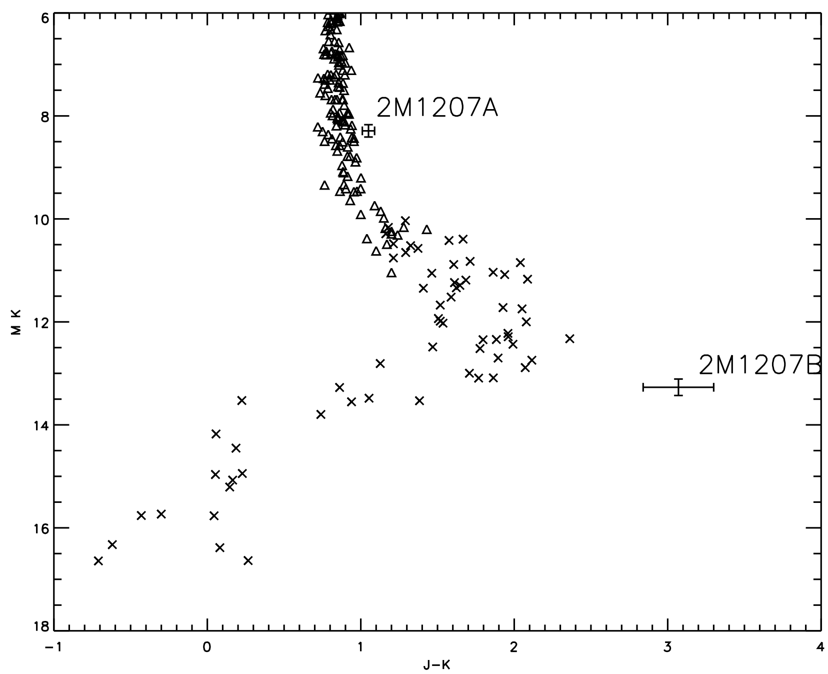

Fig. 2.— H-R diagram showing nearby field M dwarfs (triangles), field L and T dwarfs (crosses), and 2M1207A and B (points with error bars.) While 2M1207A is simply an overluminous M8 with low surface gravity as expected for a very young brown dwarf, the color of 2M1207B is much redder than field objects.

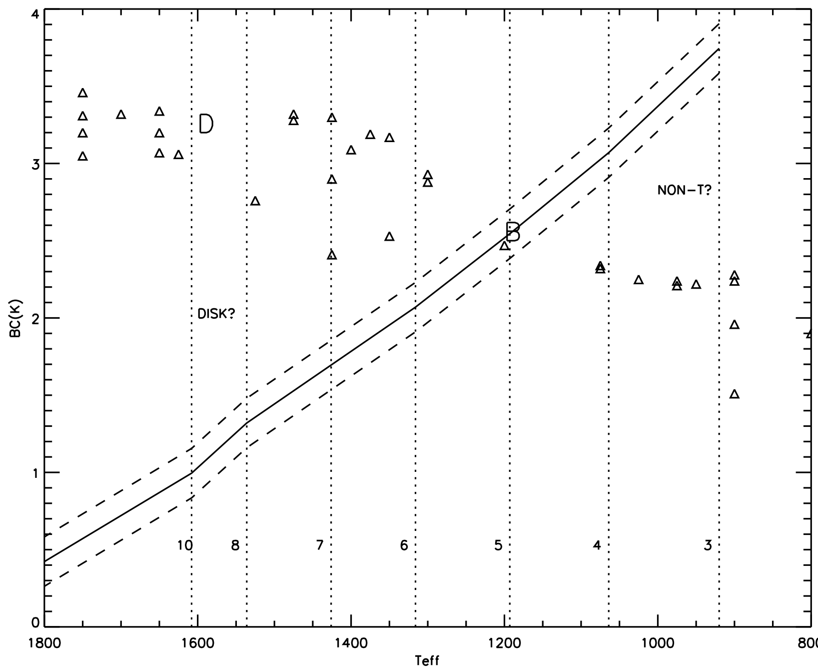

Fig. 3.— The K-band bolometric correction (solid line) required to match the observed M_K to the predicted luminosity of the 10 Myr Chabrier et al. (2000) models as a function of the model temperature. The dashed lines above and below the solid line shows the uncertainties due to the K magnitude and parallax uncertainties, but do not account for age or model uncertainties. Also shown are measured bolometric corrections for old field L and T dwarfs by Golimowski et al. (2004). The temperature predicted by different masses (in $M_{jup} = 0.001 M_{\odot}$) of the models is marked by the dotted lines. If the Chabrier et al. (2000) models are correct, 2M1207 could lie anywhere along the solid line — on the other hand, if the spectral energy distributions of young objects are similar to field brown dwarfs, then 2M1207B should lie near the region populated by open triangles. We draw attention to the point (1200K, 2.5, marked by a B), which is a plausible solution that matches the $5M_{jup}$ model. We also draw attention to the point (1600K, 3.2, marked by a D) which corresponds to the Mohanty et al. (2007) solution of an $8M_{jup}$ model — in this case, extinction due to a disk explains the difference between D and the model (1600K, 1.0) We note that the 3 jupiter mass would require a bolometric correction of 3.7 at a temperature where field T dwarfs have $BC_K \approx 2$